MICROLAMINATED FERROMAGNETIC COMPOSITES FOR MAGNETIC SWITCHING

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Abstract

We have prepared samples of multilayer ferromagnetic composites by DC magnetron sputtering. Each sample consists of a large number of polycrystalline ferromagnetic layers interspersed with an equal number of insulating layers. The thickness of each ferromagnetic layer is chosen to be less then a skin depth in the VHF frequency range. Previous authors have predicted that such a structure should remain permeable to RF energy regardless of the total thickness since the laminated structure suppresses eddy current shielding and have verified the prediction for small signal levels. In the present work, we have experimentally measured the response of our samples to large amplitude pulsed and CW signals to determine whether this class of material can be used as a high performance substitute for metallic glass in magnetic switching applications. We have produced energy in the VHF range (40 - 400 MHz) by driving our samples with a 13.56 MHz sinusoidal H field in the easy axis direction.

Introduction

Many articles have been published on the control of pulsed power by magnetic switching. Previous authors have used either metallic glass or ferrite as the saturable switching medium. The narrowest pulses reported for metallic glass have been ~ 40 nsec; ferrite is somewhat better at 5-10 nsec. In the present work we studied micro-laminated ferromagnetic composites (MLF) as an alternative to metallic glass or ferrite; we believe that this approach will have the same peak power handling capability as metallic glass but with a 1 nsec or less switching time. Microlaminated ferromagnetic composites consist of many submicron layers of well-oriented, anisotropic, soft magnetic material (such as 81:19 NiFe) alternated with similar layers of insulator to suppress eddy currents.

The desirability of using thin laminations to suppress eddy current losses in magnetic switching applications was recognized in 1981 by W. C. Nunnally of Los Alamos [1]. Submicron laminated structures have been studied for other purposes since the 1960's [2] - [4] when high vacuum evaporation was successfully used by Walser to produce laminates of up to 35 NiFe Layers with a thickness of 2000 A (.008 mils) per layer [2]. Each layer of NiFe was separated by a thin insulating layer of evaporated SiO. The basic physics of such structures is still being intensively studied for application to thin film high frequency magnetic recording heads [5] - [7].

The easy axis pulsed switching properties of single layer thin films have been studied in the nanosecond region by many authors in connection with bubble memory devices, plated wire memories, and the like. See for example [8] [9]. At least one prior study has been made of switching properties of laminated NiFe/SiO multilayer films by Humphrey, et. al. [3]; nanosecond switching times were observed.

Our present study has two main goals: (1) to develop deposition techniques that can be economically scaled up to produce this material in kilogram quantities or even tons as required for pulse power applications and (2) to measure the relevant electrical, magnetic, chemical, and structural properties of the material. This paper will report our progress toward the latter goal.

Experimental

Film Structure

Figure 1 is a 100,000X Scanning Transmission Electron Microscope (STEM) photograph of a thin section of MLF which had originally been deposited on a substrate of 0.001 inch (25 micron) Kapton® sheet. We have also obtained Auger depth profiles of our samples which reveal the details of the chemical composition as a function of depth.

The SEM photo of Fig. 2 was taken of a piece of our thickest sample--70 layer pairs (or 140 layers) which had been embedded, edge on, in epoxy and then polished. This low power (1500 X) photo should be interpreted in accordance with the accompanying sketch. The photo clearly demonstrates that the MLF is almost as thick as the (0.001 inch) Kapton substrate; our ultimate goal of course is to get the MLF thicker than the substrate.

In order to achieve 140 layers with our present sputtering system we had to stop and change sputtering targets midway through the deposition. We suspect but cannot prove that the crack running down the middle of the MLF is somehow related to the interruption.

The SEM photo shows a number of parallel dark bands approximately 1/8 inch apart; this is not the actual layer structure. At 1500X, each 1000 Å (0.1 micron) layer should appear approximately 1/7 millimeter wide and hence should be just barely resolvable. On the original Poloroid photograph, one can just barely see the true layer structure under ideal viewing conditions. The fact that the layers are so difficult to see in this photo indicates that our material has excellent mechanical integrity and structural homogeneity.

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14. ABSTRACT
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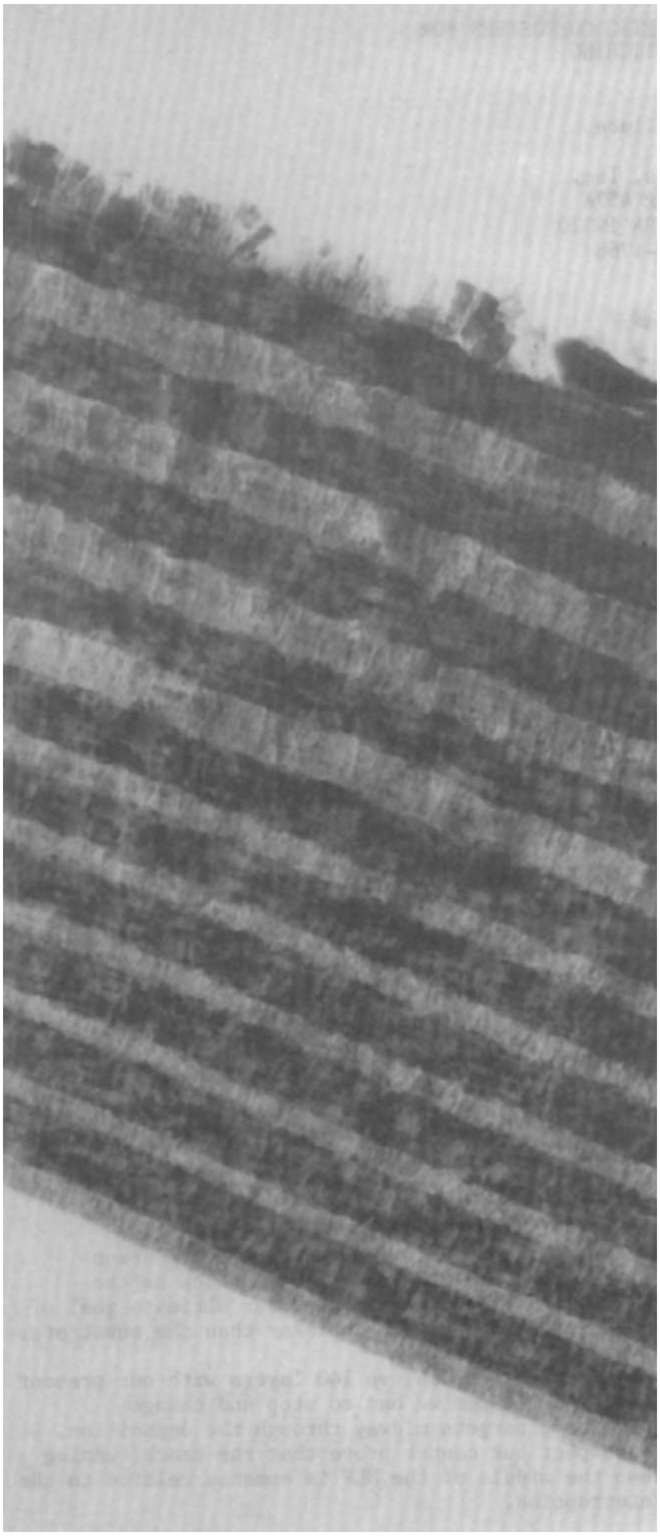


Figure 1--This is a Scanning Transmission Electron micrograph of a thin section of MLF. The dark bands are metal ("Moly-Permalloy" in this instance) and the light bands are insulator. Since the magnification is almost exactly 100000X; 1 cm on the photo corresponds to 1000 Å (0.1 micron) on the sample.

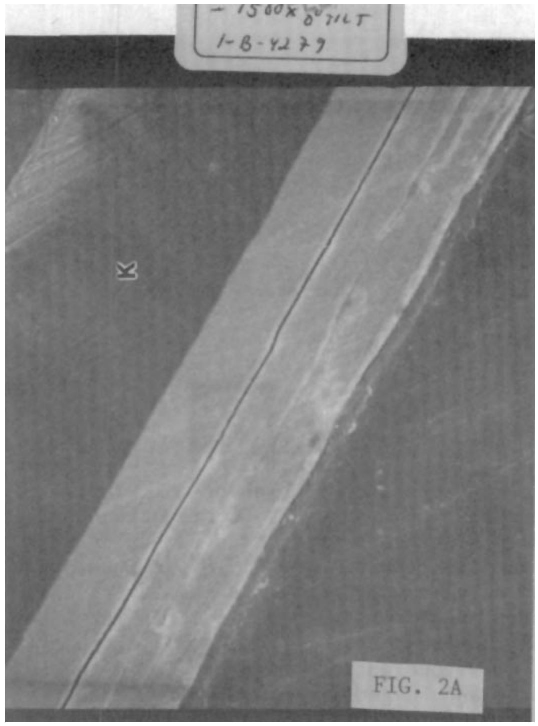


FIG. 2A

This SEM photograph of a polished MLF cross section should be interpreted in accordance with the following sketch:

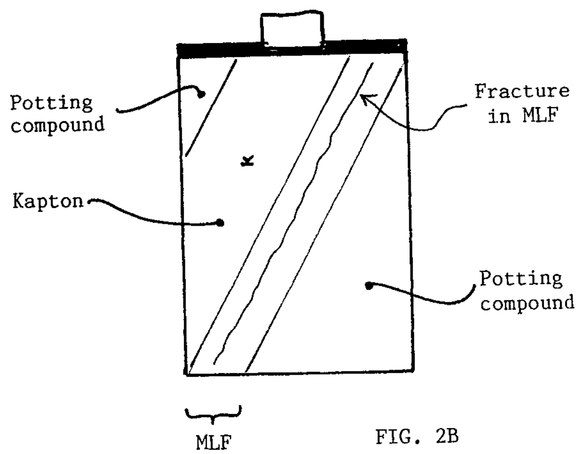


FIG. 2B

High Frequency Magnetic Properties

The high frequency magnetic properties of our samples have been characterized primarily by two techniques: The response to small-signal excitation in the hard axis (non-saturating) direction was measured in a resonant stripline cavity by the perturbation technique originally developed by Waldron [10]. Small signal RF properties are not directly relevant to the magnetic switching application; however they provide a very sensitive and very quantitative method of characterizing small, laboratory-sized samples. Our cavity system can accurately determine μ' and μ'' as functions of frequency for a 1 in.sq. sample as thin as 1000 Å (where $\mu \equiv \mu' + j\mu''$ is the small signal RF complex permeability).

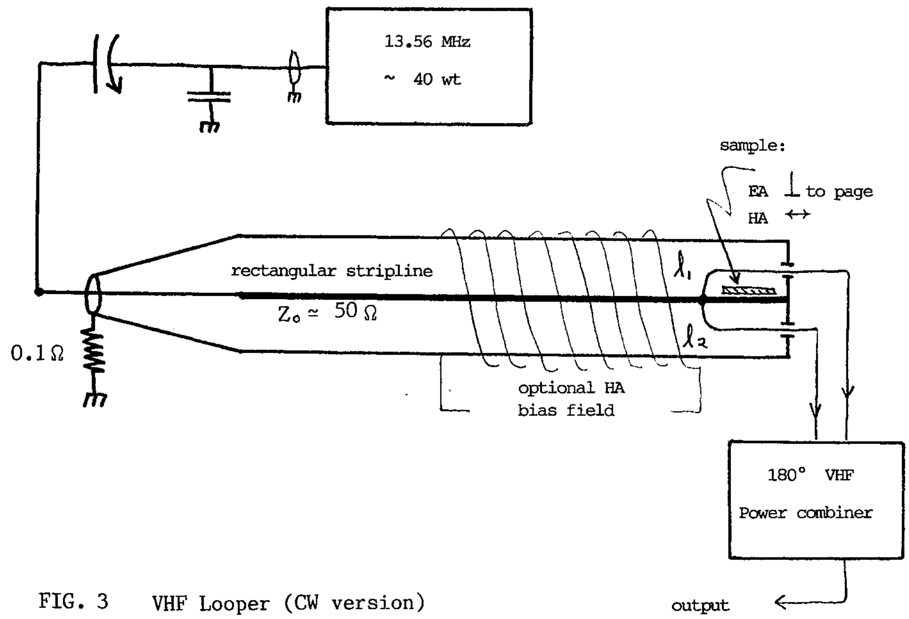
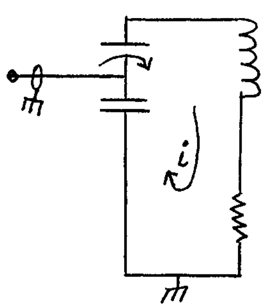


FIG. 3 VHF Looper (CW version)

We have also measured the response of our samples to a large amplitude RF field in the easy axis direction whose amplitude was sufficient to drive the samples into saturation. This equipment is sketched in Fig. 3 (above); it consists of a non-resonant shorted stripline, driven by an RF Power Amplifier at 13.56 MHz. This produces RF magnetic fields as high as 5 oe RMS across the sample. The dB/dt voltage pulse induced when the sample switches appears across loop ℓ_1 (along with a significant fundamental component due to direct coupling between ℓ_1 and the stripline). The outputs of ℓ_1 and ℓ_2 are applied to a 180° VHF signal combiner which cancels most of the fundamental (ℓ_2 serves the same function as the "bucking coil" in a conventional low frequency MH hysteresigraph). The output of the combiner can be displayed on either a wideband oscilloscope or on a spectrum analyzer.

The combined length of the stripline and its feed cable is ~ 10 feet which is approximately an eighth of a wavelength at 13.56 MHz. Hence it can be approximated as a lumped inductance with $X_L = Z_0 \tan\theta \simeq 50\ \Omega$. This creates the equivalent circuit shown below:



This "series" resonant circuit has a moderately high Q and hence the internal circulating current, i, can be very large. The 0.1Ω non-inductive resistor limits the current and also provides a convenient low impedance test point for monitoring the current by means of a voltage probe.

Fig. 3 shows a solenoid surrounding the sample end of the stripline, labelled "optional hard axis bias field"; a brief explanation of this is in order: For most of our samples we found that the easy axis switching nonlinearity was greatly enhanced by the presence of a small bias field (~ 1 or 2 oe) in the hard axis direction. Presumably this field "cocks" the spins off of dead center and removes any uncertainty about which direction they will rotate when the main EA pulse arrives. This effect has been widely reported in the prior literature; we suspect that the bias field may become unnecessary as our processing improves and we achieve samples with lower and lower easy axis coercivity. (Even if it turns out that the HA bias solenoid must be retained, this will be an insignificant additional complication in the design of an actual magnetic switching module.)

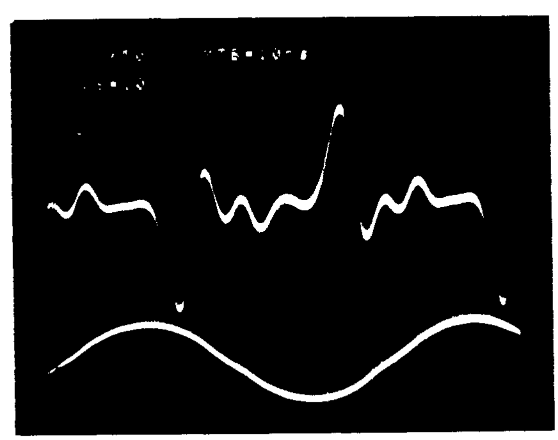


Fig. 4 This is a photo of the output of our VHF looper, displayed on the wideband oscilloscope. The lower trace shows the current waveform in the stripline (i.e. the driving H field). The upper trace shows the voltage induced in ℓ_1 when the sample switches.

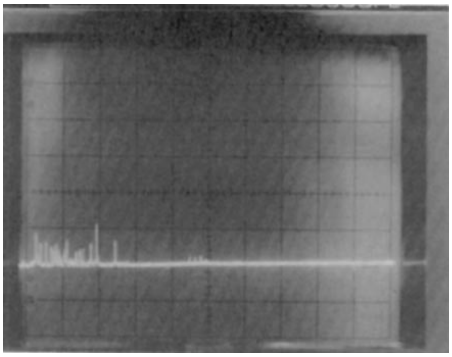


FIG. 5A Spectral output of VHF looper (with zero hard axis field)

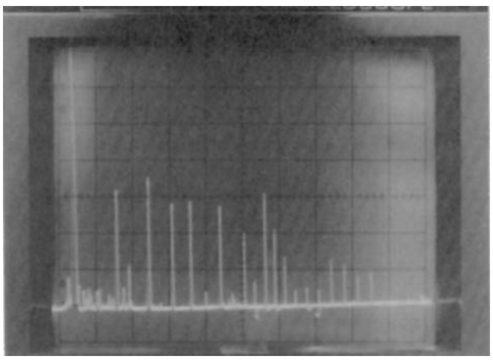


FIG. 5B As above except using optimum bias field (~ 2 oersted) in hard axis direction

Figures 5A and B were taken with a spectrum analyzer coupled to the output of the CW VHF looper. The vertical scale is completely arbitrary but it is the same for each photo. The horizontal sweep is approximately linear and extends from ~ 100 MHz to ~ 400 MHz. The highest frequency observed in B was at 393 MHz which is the twenty-nineth harmonic of 13.56.

Conclusions

We have successfully fabricated and tested samples in the range of 10 - 140 layers (5 - 70 metal layers). The layer structure of selected samples has been verified by Scanning Transmission Electron Microscope (STEM) thin section photograpy at 100,000X and the chemical composition has been studied by Auger depth profiling. The high frequency magnetic properties of the samples have been studied primarily by two techniques: (1) The small signal, hard axis permeability spectra have been measured by a standard perturbation method in a large VHF resonant cavity; and (2) The large signal, easy axis switching characteristics have been studied by driving the samples to saturation with a 13.56 MHz sinusoidal H field.

Driving the samples to saturation at 13.56 MHz (1/f = 74 nsec) produced large amounts of seventh harmonic energy at 95 MHz (1/f ≃ 10.5 nsec) and measurable amounts to at least 393 MHz (1/f ≃ 2.5 nsec). A few preliminary measurements were also attempted with large amplitude easy axis pulse excitation at a 200 Hz repetition rate. It appeared as if the samples were producing output pulses with risetimes of a few nanoseconds.

The technical feasibility of the MLF concept appears very good at this point. Our thickest sample to date has already passed one benchmark in that the mass of the deposition per unit area exceeds that of the substrate. It will be a small additional step to achieve a material wherein the volume of the magnetic fraction exceeds that of the inert portion as well. The switching times of ~ 10 nsec that we have already demonstrated fall short of the subnanosecond responses that we hope to achieve eventually and yet they already exceed the performance of commercial melt-spun metallic glass.

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